

Standardizing the Art of Electron-Beam Welding

WELDED materials are an integral part of everyday life. Appliances, cars, and bridges are all made by welding materials together. But not all welds are created equal. Welding methods vary in complexity, time, and cost, depending on a product's requirements and purpose. In electron-beam (EBeam) welding, an electron beam generated in a vacuum creates a fusing heat source that can unite almost any metals. This method produces deep welds without adding excessive heat that can adversely affect the properties of the surrounding metal.

In the nuclear energy and aerospace industries, electron-beam welding is preferred for manufacturing high-value welds—those in which defects cannot be tolerated. The Department of Energy's (DOE's) nuclear weapons complex also relies on electron-beam welding for joining critical components. Welds at this level of importance must be reliable, consistent, and reproducible, regardless of the machine used or an operator's skill.

Until a few years ago, achieving this gold standard was a major challenge. Electron-beam welding was predominantly a manual process that required an operator to pinpoint the beam's focal point, known as the "sharp focus." Because electron beams are invisible, operators could not see the beam and, therefore, could

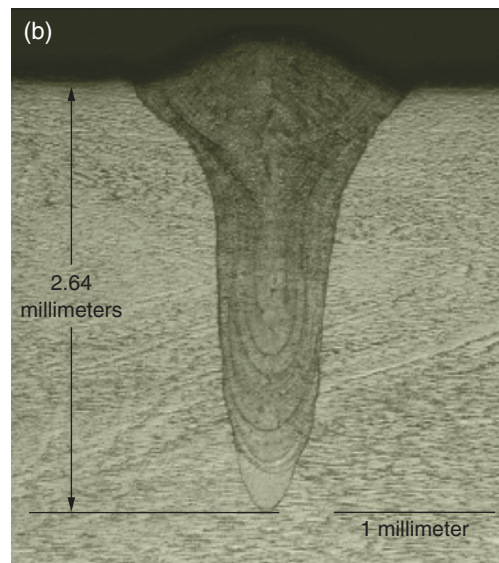
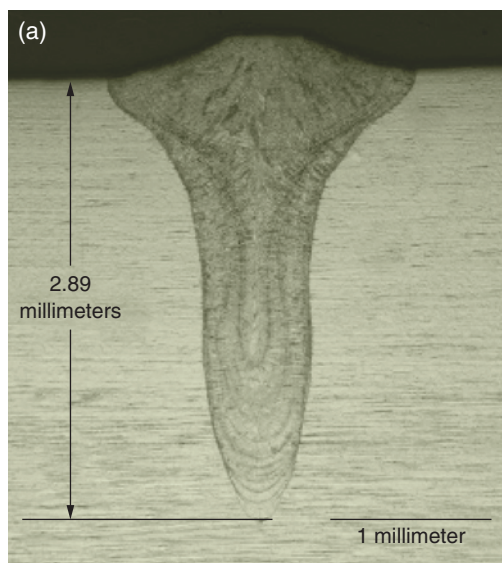
In the EBeam Profiler, a tungsten disk similar to the one shown here is placed on top of a Faraday cup to measure the current of an electron beam (EBeam) at different angles.

not focus it directly. Instead, they pointed the beam at a surrogate block of refractory metal, heating a spot until it was white hot. Then they adjusted the focus until the spot's optical brightness appeared to be at a maximum.

Operators and welding engineers agree that the sharp focus is the most difficult parameter to determine consistently because many factors can affect optical brightness. For example, an operator's optics may be dirty, or the electron beam could penetrate the surrogate block, obscuring the spot being viewed.

To improve the quality of high-value welds and mitigate weld variations, Lawrence Livermore scientist John Elmer, electrical engineer Alan Teruya, and their colleagues built the EBeam Profiler. "The profiler is a diagnostic tool that measures an electron beam's properties," says Elmer, who works in the Chemistry, Materials, Earth, and Life Sciences Directorate. Because the quality of a weld depends on a beam's power

Electron-beam parameters measured by the Laboratory's EBeam Profiler can be transferred from one machine to another, resulting in welds of similar quality. These micrographs show electron-beam welds made at (a) Livermore and (b) the Y-12 National Security Complex.



density, accurately measuring beam properties is essential for quality control.

The EBeam Profiler has a modified Faraday cup—a metal cup that catches charged particles in vacuum—to measure electron-beam currents. Computed tomography is then used to analyze a beam's power distribution. The system allows an operator to quantify the beam's power-density distribution, determine its sharp focus, and correlate machine settings with beam properties. With this tool, engineers can precisely reproduce an electron beam on the same machine time and again and transfer beam parameters from one machine to another. Thus, a weld developed for a specific step in the manufacturing process of a given part can be reproduced hours, days, or even years later.

Seventeen Is the Winning Number

An electron beam's intensity must be measured at a number of angles to obtain an accurate power distribution for computed tomography imaging. In the early 1990s, when Elmer and Teruya began their research, measuring the intensity was a time-consuming process. An electron beam was swept perpendicularly across a single narrow slit on top of the Faraday cup. A digital oscilloscope sampled the beam current captured by the cup and recorded the time-current history of the beam as it passed over the slit.

To measure an electron beam at different angles, Elmer and Teruya rotated the slit and the beam's scan direction, repeating the process as needed to gather the required data. They then saved profiles to floppy disks and manually transferred them to a VAX workstation, which created the computed tomography images. "With that method, it could take us up to a week to get

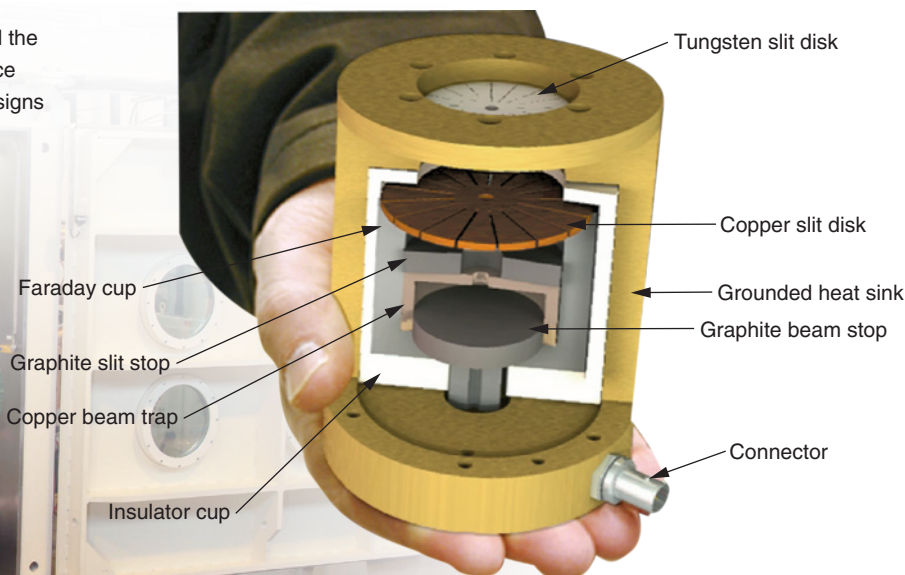
one data point," says Teruya, who works in the Laboratory's Engineering Directorate.

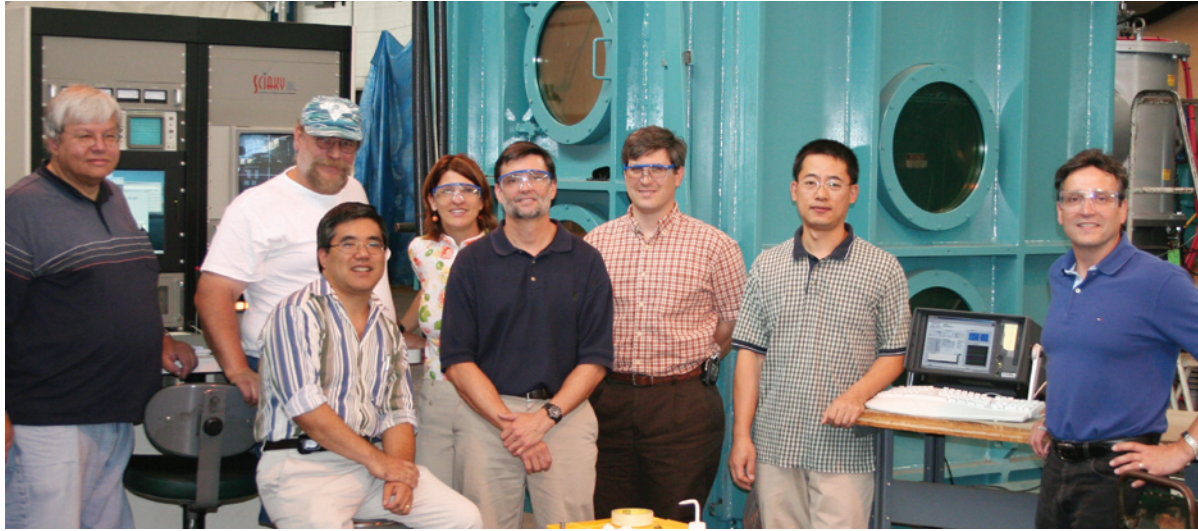
To automate the data-acquisition process, Elmer and Teruya designed a tungsten disk with a number of slits positioned in a radial pattern. Each slit is much smaller than the beam's width, and one slit is slightly wider than the others, allowing an operator to determine the beam's orientation within the vacuum chamber. Onboard deflection coils, a standard component of electron-beam welders, rapidly sweep the beam in a circular motion across the tungsten disk on top of the Faraday cup. The beam passes over each slit at a different angle, and the Faraday cup collects its current. A computer-based data-acquisition device then measures the voltage. None of the slits is directly across from another slit in the tungsten disk to ensure that separate readings are made of the beam at each angle.

Seventeen turns out to be the magic number of slits for electron-beam welders because of the beam's size and the diameter of its circular sweep. Most welders can deflect an electron beam within a circle 2.54 centimeters in diameter. With this deflection and the 17-slit arrangement, the EBeam Profiler can measure defocused beams up to 4 millimeters in diameter. In addition, a beam's size must be smaller than the distance between any two slits so that the data from one slit do not intermingle with adjacent current profiles. Thus, having more than 17 slits limits the beam size that can be measured in the defocused state.

After the beam measurements are recorded, Livermore-developed computed tomography algorithms generate a three-dimensional map of the beam's power-density distribution. This map serves as a reference for machine operators and allows

In 2006, Sciaky, Inc., in Chicago, Illinois, licensed the compact EBeam Profiler (shown at right) to reduce weld variations in critical components. Sciaky designs electron-beam welding systems such as the one below, which is used to manufacture jet engines.





The design team for the EBeam Profiler includes (from left) Mike Bell and Robert Wadman of Sciaky, Inc.; Livermore employees Alan Teruya, Annemarie Meike, John Elmer, and Todd Palmer (now at Pennsylvania State University); and James Wang and Kenn Lachenberg, also of Sciaky.

them to transfer welding parameters—peak power density, beam width, and beam diameter—from one machine to another. Data on a beam's power density can also be included in calculations that model the welding process.

The EBeam Profiler is compact and versatile. The modified Faraday cup assembly weighs less than 1.13 kilograms, has no moving parts, and works with conventional electron-beam welding machines without modifying the welder. The software can be altered to meet customers' needs, and data on a beam's power-density distribution may be incorporated into spreadsheet, plotting, and word-processing applications.

The current EBeam Profiler can handle beam powers up to 2 kilowatts. When modified to work with higher beam powers, the profiler could be used in more powerful welders or in equipment for high-current beam applications such as electron-beam coating or melting. Other proposed upgrades include custom-designed and more user-friendly interfaces and the capability to automatically focus the beam through a closed-loop feedback control system.

Annemarie Meike, a business development executive in Livermore's Industrial Partnerships Office, worked with Elmer and Teruya to meet DOE demands for the profiler and position the technology for licensing and commercial development. Says Meike, "The EBeam Profiler is a great example of how even robust technology moves into the marketplace, gaining its place incrementally over several years."

Turning toward Commercialization

DOE's Advanced Design and Production Technologies Program funded the effort to turn the EBeam Profiler into a tool for ensuring the safety and reliability of the nation's nuclear weapons stockpile. With this funding, the Livermore team delivered five diagnostic

systems to DOE laboratories and manufacturing sites, including Los Alamos and Sandia national laboratories, the Y-12 National Security Complex, and the Kansas City Plant. The Laboratory subsequently worked with DKO, Inc., in Castro Valley, California, on a contract-by-contract basis to manufacture additional units for other government agencies.

Advances in technology allowed Elmer and Teruya to revise the profiler's design so that data acquisition and computed tomography can be completed on a single computer. As a result, the time needed to measure the beam and review the results has decreased from several days to mere seconds. "That change has made the profiler a commercially viable diagnostic," says Teruya. In 2006, Sciaky, Inc., in Chicago, Illinois, licensed the profiler to investigate the properties of electron beams in the company's welders and to determine customer interest in using the diagnostic. The company now holds a full commercial license and sells the technology under the name EBeam 20/20 Profiler.

"Customers in the nuclear and aerospace fields are placing more emphasis on quality control," says Elmer. "It is only a matter of time before such diagnostics become standard additions on machines used to manufacture high-value and safety-critical electron-beam welds."

—Caryn Meissner

Key Words: computed tomography, electron-beam (EBeam) reproducibility, EBeam Profiler, electron-beam welding, modified Faraday cup, power distribution, quality control diagnostics, sharp focus.

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